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FLOW VISUALIZATION AND QUANTITATIVE GAS DENSITY MEASUREMENTS IN RAREFIED GAS FLOWS

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-62-793

December 1962

Directorate of Engineering Test
Deputy for Test and Support
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 1426, Task No. 142610

(Prepared under Contract No. AF 33(616)-8145
by Cornell Aeronautical Laboratory, Inc., Buffalo, New York;
Robert C. MacArthur, Leroy M. Stevenson and John Budell, Authors.)

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FOREWORD

This report was prepared by Cornell Aeronautical Laboratory, Inc., Buffalo, New York under USAF Contract No. AF 33(616)-8145. The contract was initiated under Project No. 1426, "Experimental Simulation of Flight Mechanics," Task No. 142610, "Development of Experimental Aerodynamic Testing Techniques." The work was administered under the direction of the Directorate of Engineering Test, Deputy for Test and Support, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Mr. Dallas Searcy was the project engineer.

This final report covers work done from 1 March 1961 to June 1962 and represents a continuation of earlier work on the same research reported in Ref. 3.

This effort was performed by the Applied Hypersonic Research Department of the Cornell Aeronautical Laboratory, with Mr. Robert MacArthur as the principal investigator. The authors wish to acknowledge the contributions of their colleagues Dr. Dennis Malone of the Applied Physics Department for the mathematical analysis presented as Appendix A, and Dr. Donald Boyer of the Applied Hypersonic Research Department for the treatment of the electron beam as a diagnostic technique in hypervelocity flows presented in Appendix B.

ABSTRACT

The use of an electron beam to stimulate emission from a gas with the resultant beam intensity providing a measure of point-by-point gas density has been investigated. The tests have been conducted in the 1 to 200 micron pressure range, at standard temperature, employing a 5 to 20 kev electron beam. Analysis was performed by photographing the beam at conditions of varying density, and examining the film by means of a microdensitometer. A low-cost electron gun capable of projecting a 20 kev, 500 microampere beam across a 24-inch test chamber was successfully developed.

The results of the program indicate that at the beam voltages employed, scattering of the electrons by the atoms of the gas severely limits the particular technique used.

The analytical and experimental results of the program indicate that gas density measurement and flow visualization may be possible by employing a more energetic electron beam. By observation of the beam-excited emission spectra, it is possible to measure the rotational and vibrational temperature of the nitrogen molecules as well as the number density of nitrogen molecules in the gas. Further investigation of this latter electron beam technique as a diagnostic technique in hypervelocity flows is recommended.

This technical documentary report has been reviewed and is approved.

George A. Kirsch

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Colonel, USAF
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NOMENCLATURE

c	Velocity of light
D	Film density = $\log_{10} \frac{1}{T}$
d	Thickness of gas (cm.)
E	Exposure, product of illumination and the time of exposure
e	Electron charge
m	Electron mass
N	Number of gas molecules per cc.
T	Transmittance, the ratio of the radiant power transmitted by the film to the total radiant power incident in the film
V	Velocity of incident electron
Z	Atomic number
β	Ratio of electron velocity to the velocity of light ($= V/c$)
γ	Slope of the film density - log exposure curve for developed film
ρ	Gas density, mass per unit volume
$\pi\rho^2$	Total collision cross section of a gas molecule for electrons

INTRODUCTION

Many techniques exist for photographically recording flow patterns in wind tunnels. Among the more common are the shadowgraph, schlieren, and interferometry techniques. These normally require density gradients corresponding to pressure differences of several hundred microns at standard temperature, and thus are unsatisfactory for use in the region of 1 to 200 microns pressure that is required in this investigation.

Several electromagnetic radiation techniques have been employed using spectral regions in which the test gas shows appreciable absorption. For example, molecular oxygen strongly absorbs ultraviolet in the wave length region of 1470 Angstroms; near-ultraviolet and X-radiations have also been used.[1] These absorption techniques all suffer the same severe limitation in that they yield integral values for densities over the total path of the beam; thus, it is not possible to extract density information at a given point in the gas. In order to obtain a measurement of local density, it is necessary to cause a point in the flow field to emit energy that may be detected in a direction that does not include the line or plane of the stimulus.

The principles of the electron-beam technique may be summarized as follows: (1) the test gas is excited to emit by the electron beam, (2) the radiation system of the gas has an extremely short lifetime, (3) at low densities collision quenching is relatively unimportant and does not affect the intensity of the net excited emission; therefore, the light output is a function of the number of atoms excited, i.e. of the density of the gas. Thus, a relationship between gas density and beam-stimulated emission may be obtained. Correspondingly, by projecting a narrow beam into the test gas and measuring the intensity along its axis, a measure of gas density distribution may be obtained. A plane or selected volume of the gas may be studied by providing a scanning system for the beam.

Studies at the University of Toronto Institute of Aerophysics (UTIA)[2] directed to the measurement of gas density with the electron beam technique employed an optical system and photomultiplier tube to examine a small length of the beam. Their initial results were encouraging; they found that for air densities corresponding to pressures of the order of 100 microns of mercury and below (at room temperature) and projected beam path lengths of about 10 centimeters, electron energies of 10 to 20 kev were sufficient to generate an "essentially unattenuated beam."[2] The work done at the UTIA further demonstrated that the total light output from a particular

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small volume of gas in the path of a constant voltage-current electron beam was essentially linear with gas density up to pressures of 200 microns. It was further noted that the energy extracted from the beam by the gas was small.

The encouraging UTIA results indicated that further investigation of the electron-beam probe technique for studying local gas density in a hypersonic flow field was warranted. Although no quantitative measurements were made of local gas density in a hypersonic flow field utilizing the electron-beam probe, photographic records were made of the light emitted when the electron beam passed through a shock. On the basis of preliminary calculations, it appeared possible to develop the electron-beam probe technique so that flow patterns could be observed in a hypersonic flow field and that quantitative measurements of the local density could thus be obtained.

In February 1960, a development program on the electron-beam probe technique was begun at CAL. The initial effort was concluded in November 1960, and the results are presented in Ref. 3. In March 1961, the program was continued. The purpose of this program was to investigate the feasibility of this technique for displaying flow patterns and for measuring local gas density. Theoretical development and design studies were to be conducted to (a) determine the relative merits of scanning, non-scanning or multibeam scan techniques; (b) produce a reasonably economical electron gun with beam characteristics suitable for use in experimental studies; (c) investigate and determine the limitations of receptors and recording devices presently available. Ultimate application was to be to the ASD low-density tunnel.

This report discusses the development of the electron gun, the results of a series of static beam characteristic measurements performed in the 24-inch diameter test chamber in the pressure range of 1 to 200 microns, and recommendations for the use of the probe and for additional research and development.

EXPERIMENTAL TECHNIQUE

General Description of Apparatus

The apparatus shown in Fig. 1 consists of: a test chamber 2 feet in diameter and 2 feet long, an electron gun, vacuum pumps (two mechanical and two oil diffusion), a high-voltage power supply for the electron gun and pressure-measuring equipment consisting of a McLeod gage, an ionization gage, and several thermocouple gages. Deflecting coils and permanent magnets for focussing the electron beam, and cold traps, special valves and baffles to maintain gas purity were also employed.

Electron Gun Vacuum System

Pressures of the order of 10^{-6} mm of mercury are desirable for proper electron gun performance. Suitable cold traps and baffles in the vacuum system are necessary to reduce the possibility of oil vapor migration from the pump into the electron gun vacuum system.[4] The vacuum equipment consists of a 2-inch, 3-stage, water-cooled fractionating oil-vapor diffusion pump with a capacity of 50 - 55 liters/second, as measured at the mouth of the baffle valve, and has an ultimate vacuum capacity of 5×10^{-7} mm Hg. The backup pump is a mechanical-rotary type having a displacement of 48 liters/minute. A moisture trap, utilizing phosphorous pentoxide as a desiccant, is mounted directly above the rotary backup pump inlet. The cold trap has a fluid capacity of 0.9 liters. Liquid nitrogen is used as a refrigerant; one filling lasts for a period of approximately 16 hours of operation. The water-cooled baffle-valve reduces undesirable "back-streaming" of the diffusion pump oil vapors without undue reduction of pumping speed. Cooling water flow of 0.5 liters/second at 15°C is required for the proper operation of the diffusion pump.

The electron gun pressure was measured by a hot-cathode ionization gage; and the diffusion pump forepressure was monitored by a thermocouple gage. To couple the electron gun to the vacuum system and the test chamber, commercial pyrex-glass piping and accessories were used. A teflon bellows provided vibration isolation between the top of the oil diffusion pump and the electron gun vacuum system.

Test Chamber Vacuum System

The range of air densities to be studied was 3.1×10^{-9} to 6.3×10^{-7} slugs per cubic foot corresponding to pressures of 1 and 200 microns of mercury at standard temperature. The initial rough pumping of the test chamber, whose volume is 7 cubic feet, was accomplished by means of a Welch Duo-Seal two-stage mechanical rotary vacuum pump with a free-air

capacity of 140 liters per minute. A 2-inch, 3-stage, water-cooled fractionating oil-vapor diffusion pump was added to the test chamber vacuum system to permit study of electron beam performance at pressures of the order of 1 micron and to facilitate the use of a dynamic pressure chamber between the test cell and electron gun. Therefore, by suitable valving, the rotary mechanical pump served dual purposes; it provided rough pumping of the test cell from atmospheric pressure, and was also a forepump for the oil diffusion pump.

The test chamber pressure was measured by a cold-trapped McLeod gage. Errors due to the instability of calibration of the thermocouple gage led to the addition of the McLeod absolute pressure gage. Although this instrument provided noncontinuous readings of pressure and indicated partial pressure (rather than total pressure), it retained its high accuracy and was used as a standard reference instrument against which all other gages were calibrated.

Dynamic Pressure Chamber Performance

In order for the electron gun to function reliably, it had to be exhausted to and maintained at a vacuum of the order of 10^{-5} mm mercury. The range of densities to be studied corresponded to pressures of 1 to 200 microns of mercury at standard temperature. Further, the electron beam had to be projected from the gun into the test cell through an orifice rather than through a thin window. A single orifice seriously limited the vacuum attainable in the gun.

A dynamic pressure stage as suggested by B. W. Schumacher[14] was installed between the test cell and electron gun and maintained at low pressure by a separate oil diffusion vacuum pump. The performance of this dynamic chamber is shown in Fig. 4.

Electron Gun Power Supplies

An rf high-voltage power supply was used to supply anode potentials for the electron gun. The output of the power supply was continuously variable from 5 to 30 kv, with regulation better than 0.5% and provision for negative polarity output; its current capacity was 1 ma. A special voltage supply was available to provide a variable electrostatic focus voltage control for the electron gun.

The electron gun heater voltage was supplied by a special high-voltage

insulated transformer.* The heater and cathode elements were at high negative voltage with respect to ground. The secondary was wound with high-voltage cathode-ray-tube anode lead wire to provide insulation rating of 40 kv between the primary and secondary windings. A variac connected to the primary provided the voltage adjustments necessary for cathode activation as well as for normal operation of the heater.

Five microammeters were employed to measure the electron gun element currents. Provision was made for adjustment of the individual element voltages. Cathode, grid No. 1, grid No. 2, and focus-anode currents were measured to give a quantitative indication of the performance of the electron gun. In addition, electron-beam current was collected and measured at a cup-shaped receptor in the test cell.

Electron Gun

A major part of the effort of this project was devoted to the successful adaptation of an economical, commercially available electron gun. Television picture tubes have such electron guns; they are therefore readily obtainable.** They are produced with a broad range of ultor voltage (from 5 to 80 kv), heater voltage, spot size, and cathode material; in addition, magnetic and/or electrostatic focussing may be employed.

The electron guns used on this project can generate a 1 mm diameter beam of up to 20 kv with an electron current in excess of 500 microamperes projected into the test chamber. The gun assemblies are of the 110° magnetic deflection, electrostatic-focus type furnished with a standard oxide-coated cathode with an ultor voltage rating of 20 kv and heater rating of 6.3 volts. These guns have a grid No. 1 aperture of 0.025 in. diameter. Spot size, or beam diameter can be controlled by the aperture diameter of grid No. 1.

Initial attempts at CAL, as reported in Ref. 3, to operate oxide-coated cathode electron guns in a continuously pumped vacuum system were not successful. It was found during the current phase of this project that by employing Shell Apiezon oil type C in place of Dow Corning silicone oil type 704, it was possible to operate these same electron guns successfully. The adverse effect of decomposition of silicone vapor on cathode surfaces has been reported in the literature (Ref. 6). When an organic vapor that has been deposited on a surface is decomposed by electron bombardment, a solid residue may remain. With most organic vapors, this deposit may be electrically

* Superior Electric Co. "Flexiformer" type TP150 packaged transformer.

** Superior Electronics Corp., 208-212 Piaget Ave., Clifton, New Jersey, is the manufacturer of the electron guns used for this project.

conducting or insulating depending on the nature of its formation; with the silicone fluids, however, the deposited film is insulating silica which greatly attenuates the cathode emission of the tube. Therefore, although recommended generally for high vacuum work, silicone fluids cannot be used in the electron-gun oil diffusion pump system.

Cathode Activation

Initially, the oxide-coated cathode does not show any appreciable electron emission and therefore must be activated. The activation process required depends upon the cathode coating; in general, it consists of heating the filament for several minutes at a temperature of 1000°K to 1500°K which is well above the normal operating range, followed by a period of operation at a lower temperature for a longer time with the anode voltage applied. During this treatment, the emission increases rapidly to its maximum value corresponding to full activation of the cathode.

Electron Gun Life

The operating life of the electron guns averaged in excess of 80 hours. Actual life was dependent upon the number of times the cathode had to be re-activated and the number of times the gun assembly was exposed to atmospheric pressure. At the termination of each day's operation, the electron gun was kept at high vacuum. Prior to use, new electron guns were stored in a dry, clean atmosphere. (Use of a desiccating cabinet is highly recommended.) Electron guns could be replaced and the system pumped down within one hour.

Electron Gun Operation

After cathode activation, cathode currents of the order of 1500 microamperes were available at a heater potential of 6.5 volts. As the gun aged, increases of heater voltage were necessary to maintain this cathode current, until a value of 12.5 volts had been reached. At this voltage, grid No. 1 emission became apparent as an increase in spot size, and replacement of the electron gun assembly was necessary.

Although the electron guns were of the electrostatic focus type, additional electromagnetic focussing at the region of grid No. 1 was employed to further reduce the spot size. A continuous coating of aquadag* was applied to the inside

*Aquadag is a colloidal suspension of graphite. Secondary emission of electrons is low due to the high work function of graphite.

surface of the glass gun walls extending to the orifice in order to reduce static charge effects. A small window permitted visual alignment of the spot at the first orifice, which was accomplished by means of a permanent magnet located near grid No. 1. Adjustments of grid No. 1 bias, grid No. 2 and focus-anode voltages were then made to provide a maximum current at the electron-beam collector cup in the test chamber. In the typical case of 1500 microampere cathode current, about 600 microamperes maximum could be obtained as beam current. More precise mechanical and optical alignment of the electron gun with respect to both orifices would, of course, realize greater net beam currents.

Since a large percentage of the cathode current was lost because of imperfect alignment, X-rays were produced as a result of electron impingement on the metallic area around the orifices. Although the operating voltages were kept below 24 kv, the measured X-ray radiation intensity was of the order of 2.3 mr/hr. At higher operating voltages, the X-rays that would be produced would be hard enough that shielding would then be required to protect against the radiation hazard. The personnel in charge of the operation of the high-voltage electron gun were provided with X-ray film badge monitoring service as a measure of protection.

Fluorescence due to secondary emission from the wall due to impingement of the electron beam was pronounced at higher densities during the initial experiments. Treatment of the test chamber walls and the electron beam receiver cup with aquadag substantially reduced this secondary emission.

The sequence of operation was as follows: The test chamber was secured and evacuated; the electron gun was activated and the electron beam injected into the test chamber; focussing and collimation were accomplished with the test chamber pressure at 1 micron. After the electron beam was adjusted, the density of the gas in the test chamber was brought to the desired value by adjusting the pressure at a known temperature. The fluorescent beam was then photographed and the resulting photograph was examined on the microdensitometer.

DISCUSSION

At the time this project was initiated, it was contemplated that an image converter would be made available by ASD for use on this project. It turned out that the image converter was not supplied. Photomultiplier techniques of data recording had previously been studied (Ref. 3) and, although there are advantages to their use (mainly sensitivity and convenience in data recording and processing), it was elected to use photographic techniques for at least the preliminary studies. The primary advantage leading to this initial choice was the ability to obtain characteristics of the entire beam as projected into the test section with a very simple apparatus and in a form which lent itself to qualitative analysis. The early photographs indicated certain basic (and unexpected) limitations of the technique arising from an apparent attenuation due to electron scattering by the gas. Subsequent effort was directed to the study of these characteristics of the beam and methods of circumventing the difficulties rather than diverting effort to setting up photomultiplier scanning techniques.

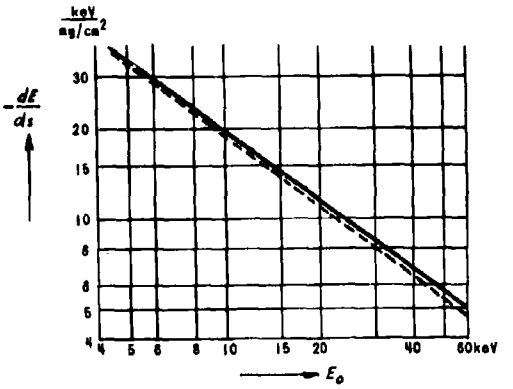
A comparison of the ultimate limits of the two detection techniques may be obtained from Ref. 13, which discusses in detail the sensitivity of recording devices. In this reference, it is stated that the responsive quantum efficiency for an S-5 photocathode as used in a 1-P-28 photomultiplier is 18% as compared to a detective quantum efficiency of 1% for Royal X film at optimum exposure (these data are compared at a wavelength of 4000A°). Thus, equal sensitivity may be obtained with the two devices at a gas density ratio of 1 to 18.

Experimental Data

Figure 5 is a series of photographs of the electron beam showing the effect of varying the exposure with the test chamber density, electron gun voltage, and electron current held constant. The values of these parameters are given in Table I. It may be noted that the apparent beam attenuation of Run 89 is, in reality, beam spreading as shown by the increased beam width with larger exposures. A word of caution is in order in interpreting these photographs. The dynamic range of the film is limited; the central axes of the pictures with the longer exposures are overexposed, that is, the exposed film is beyond the linear portion of the D-log E curve, giving incorrect data on the relative energy of the central axis compared to that off the axis.

Figure 6 is a series of four pictures that show the effect of varying the exposure inversely with the gas density, resulting in a constant exposure at the start of the beam. Attenuation of the beam is seen to increase as the density of the gas in the test chamber is increased. This attenuation is due to the absorption of energy from the beam by the gas molecules, and the scattering of the electrons by the gas. Calculation of the specific energy loss, dE, of the electrons along the projected path length of the beam shows that

the fraction truly absorbed is quite small and is not sufficient to account for the attenuation. The following figure is a plot of the specific energy loss per unit length of the true path of the electrons. For example, for a path length of 50 cm and a gas density $\rho = 8.2 \times 10^{-8}$ gm/cm^3, (62 microns Hg), $\Delta E_{average}$ = 45 volts. This loss is negligible with respect to the initial beam energy of 10 kev. Since the photographs indicate a severe attenuation, it is evident the effect is due to scattering of the electron beam by the gas.



Specific energy loss dE of electrons along the true path length ds as a function of energy E.
Solid line: Bethe's theory.
Points and dotted line: Grun's measurements of the flourescence yield in air excited by electrons.

(Reproduced from Ref. 2)

Figure 7 shows a single photograph of a 20 kev beam of 275 micro-amperes current in the test chamber at 65 microns air pressure. Figure 8 shows the microdensitometer record of 10 equally spaced scans across this beam trace. It is noted the traces become broader and peak intensity drops as the scan proceeds toward the end of the beam demonstrating the degree of scattering under these conditions.

In order to reduce the data obtained from the microdensitometer, it was necessary to determine the Density (D) vs log Exposure (E) plot for the particular film used. Three types of photographic films, Royal Pan, Royal Ortho, and Royal Blue Medical X-ray were employed in the experimental investigation. Observations made during the experimental investigation indicated that the Royal Pan and Royal Ortho films were very nearly equal and with normal development a γ (slope of the density, D, vs log exposure curve) of one was obtained. The Royal Blue film was approximately twice as sensitive as the Royal Pan and Royal Ortho films. Normal development of the Royal Blue

film resulted in a γ of approximately four. The Royal Pan and Royal Ortho film had a wider dynamic range than the Royal Blue. Since the slope, γ, of the D-log E curve is a function of the film, the development, and the spectral sensitivity of the film, the following procedure was employed. The light from the fluorescent gas was used to obtain the D vs log E data by holding the test chamber parameters and electron beam parameters constant and taking a series of pictures with a varying exposure. The density of each negative was read at the electron gun end of the beam and the D vs log E plot constructed from these readings.

Figure 9 shows the D vs log E plot obtained. Figure 9 also shows that γ varied with development as evidenced by the picture series, 157, 158, 159 and 160 which apparently received a development different from pictures 149, 150, 151, and 152. Caution was exercised in the development procedure; however, since the time of development, the temperature of the development bath, the amount of agitation and depletion of the chemicals all have an effect on the γ, precise control is difficult.

Closer control of development would have required automatic equipment, and was not felt to be justified by the requirements of this investigation; using the γ obtained from one group of pictures to obtain values of intensity along the beam for pictures within the group, the variation of film development was circumvented. Figure 10 is an example of the lengthwise variation of light intensity normalized to the value at the start of the beam. A correction[8] of $\cos^4 \theta$ was applied to the data to allow for fall-off of the illumination on the film plane. θ is the angle between the normal to the camera focal plane and the ray from the particular point on the beam being measured, and in these experiments had a maximum value of 11°. Figure 10 shows that the peak intensity; i.e., intensity of the axis of the beam, may be expressed as $I_x = I_o e^{-\alpha x}$ where α is a combined scattering and absorption coefficient.

Scanned Beam

Figure 12 shows the results (Table I, Run 183) obtained when the beam was scanned by moving the camera during exposure in a direction perpendicular to the plane which contained the beam axis and the optical axis of the camera. The densitometer readings of % transmission (Fig. 13) show recovery of almost a uniform film exposure over the length of the beam. Note that the slope of the top of the records is explained by the nonuniform rate of scanning by the camera as shown in Fig. 11. The rounding of the leading and trailing edges and the spreading of the base of the records in Fig. 13 is due to the scattering of electrons by the gas.

The qualitative effect of a density variation in the beam path was examined. A jet of air was introduced in the chamber perpendicular to the camera

and beam axis. The results are shown in Fig. 16. The air jet exit was within 0.25 inches of the beam. The chamber density corresponded to four microns pressure at standard temperature, and the local density in the jet was of the order of 5000 microns. Two effects are apparent: first, an increase in intensity on the beam axis; and second, a widening of the beam as a result of increased gas density in the scattered part of the beam, providing enough luminosity to register on the film.

From the foregoing, it was apparent that electron scattering was the principle cause of loss of light intensity at the far end of the beam axis. Examination of the data indicated that equal exposure at both ends of the beam could be obtained by moving the beam at right angles to its axis, thereby providing an integral of the light from the spread beam. An equivalent procedure, and the one actually employed, was that of moving the camera instead of the beam.

Spectral Characteristics of the Beam

Spectral measurements were made of the radiation induced by the electron beam to verify the source of the emission and the absence of impurities as may have arisen from pump oil and/or mercury vapor. The measurements were made in air at 50 microns pressure and 20 kv accelerating voltage.

A simplified optical setup was used. Spectra were taken by placing a transmission grating in front of the camera lens. The camera was focused on a slit which was illuminated by the beam radiation; images of the slit were recorded of the undeflected light and the first-order spectrum of the grating. The camera focal length was adjusted to give maximum dispersion in first order consistent with the size of the film. Comparison spectra were recorded from a fine-line mercury source to calibrate the wavelength scale of the system and to establish the wavelength response of the film. All principal mercury lines between 3650 and 6000 Angstroms were recorded.

The spectrum of the beam induced emission showed three prominent lines with some evidence of banded structure between them. Although the determination of wavelengths was limited to about ten Angstroms, the three lines were shown to correlate very well with three vibrational bands at wavelengths of 3914, 4278 and 4709 Angstroms in the nitrogen-ion first negative system. These band systems correspond to transitions from the ($v' = 0$) vibrational level of the upper electronic state, $N_2^+ B^2 \Sigma_i^+$ to the ($v'' = 0$, 1 and 2) levels of lower electronic state, $N_2^+ X^2 \Sigma_g^+$. The structure of these bands consists mainly of two branches, one of which is headless and widespread, while the other is headforming and therefore is photographed as a line under low dispersion.

Because this experiment was designed only to ascertain the origin of the radiation, no attempt was made to measure relative or absolute intensities. It can be concluded from this simple test, however, that the radiation results from the N_2^+ or N_2^+ first negative system transitions as indicated and as expected.

CONCLUSIONS

The two principal difficulties with the electron beam technique for flow visualization and point-by-point gas density measurement, for the conditions outlined are (1) low light emission under low-density conditions and (2) severe light scattering under higher-density conditions. Scanning the beam with a moving camera (with shutter open) to simulate a test section traversed by an electron beam greatly improves the constancy of the picture density relative to nonscanned records which have severe beam attenuation. The scanning, however, does not eliminate the loss in spatial resolution caused by the spreading of the electron beam. There is a dependence of the light given off at any point along the beam on the gas density through which the beam has traveled and indeed to a lesser extent upon the gas density through which the beam traverses in adjacent paths as discussed in Appendix A. The effect of greater or less scattering from adjacent higher or lower density regions will result in halation. The resulting loss in resolution is potentially limiting.

Nevertheless, the technique may have application to the measurement of gas density in a hypersonic test facility, and additional research is recommended. For example, the direct measurement of the gas density at hypersonic speeds, even in a tunnel without a model in the test section, is difficult. The electron beam can be employed to provide this determination by observing the fluorescent characteristics of the beam in the tunnel when there is no airflow, but in the density range of interest, and then measuring the beam characteristics during the desired flow conditions. Microdensitometer analysis of the negative of the scanned beams, and the calibration provided by the static (no-flow) data, thus enables the determination of stream density during the hypersonic flow condition.

This technique may not be limited to the tunnel-empty (i.e., no model) condition since the scanning integrates the effect of scattering. Thus, although severe scattering of the electron beam may occur in the passage of the beam through a strong shock pattern, or close to a model, the comparison of the beam characteristics for the static and dynamic conditions (at the same mean value of stream density) around a model may provide quantitative data on the density distribution during conditions of hypersonic flow.

The analytical and experimental results of the program indicate that gas density measurement and flow visualization may be possible by employing a more energetic beam. By observation of the beam-excited emission spectra, it is possible to measure the rotational and vibrational temperature of the nitrogen molecules as well as the number density of the nitrogen molecules in the gas. A discussion of this technique is presented in Appendix B.

In summary, an electron-gun system was successfully developed that was capable of projecting a collimated electron beam across a 24-inch diameter

chamber at pressure-densities in the 1 to 200 micron range. The scattering of electrons by the gas and the model was the most critical problem; scanning of the beam provided improved results. Additional static and dynamic tests with selected model configurations, as well as further analysis of the beam-emission spectra are required to properly evaluate the technique.

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APPENDIX A
MULTIPLE SCATTERING OF ELECTRONS IN A GAS

Consider the case of a uniform gas containing N molecules per cc.

The total collision cross section of a molecule can be denoted by $\pi\rho^2$ and the thickness of the gas by d (cms). (The approximation will be used that the path length of the electron is equal to d.)

Then the average number of collisions made by one electron in traversing the scatter is

$$\nu = \pi\rho^2 N d \tag{1}$$

The probability that an electron suffers n collisions is given by the Poisson distribution

$$W(n) = \frac{e^{-\nu}\nu^n}{n!} \tag{2}$$

It is a property of Legendre Polynomials that the average value of the polynominal after n impacts is equal to the n^{th} power of the average value after one impact provided that the scattering law is cylindrically symmetrical

i.e. $$\left\langle P_\ell(\cos\theta)\right\rangle_{AV} \quad \left\langle P_\ell(\cos\theta_1)\right\rangle_{AV}^n$$

So the final total average will involve all possible values of n. If the average is denoted by G_ℓ, then

$$G_\ell = \sum_{n=0}^{\infty} W(n) \left\langle P_\ell(\cos\theta)\right\rangle_{AV}^n \tag{3}$$

This function determines the angular distribution of the emerging electron. Hence the intensity of scattering per unit solid angle in the direction θ is given by

$$f(\theta d) = \frac{1}{4\pi} \sum (2\ell+1) G_\ell P_\ell(\cos\theta) \tag{4}$$

Now on substitution for $W(n)$ in (3)

$$G_\ell = \sum e^{-\nu} \cdot \nu^n \left\langle P_\ell(\cos\theta_1)\right\rangle_{AV}^n / n! = e^{-\nu Q_\ell} \tag{5}$$

where

$$Q_\ell = 1 - \left\langle P_\ell(\cos\theta)\right\rangle_{AV} \tag{6}$$

Now the actual scattering law involved must be examined. This is best expressed in terms of $y = \sin \theta/2$

Then the distribution of scattering for a single collision normalized to one incident electron per cm^3 can be written as

$$2\pi I(\theta) \sin\theta \, d\theta = \frac{2\pi K^2 g(y)}{y^3} dy \tag{7}$$

where

$$K = \left(\frac{Ze^2}{mc^2}\right) \frac{(1-\beta^2)^{1/2}}{\beta^2}$$

Z = nuclear charge

e = electron charge

m = electron mass

c = velocity of light

$\beta = V/c$

V = velocity of incident electron

i.e., in the case of a 100 kev electron incident in air, which is mostly nitrogen, of $Z = 7$, $\beta^2 \sim 0.75$,

$$K^2 = 1.724 \cdot 10^{-24} \tag{8}$$

for 20 kev, $K^2 = 1.41 \times 10^{-24}$

The function $g(\bar{y})$ is a factor applied to allow for the screening of the nucleus by the orbital electrons and has different values for the different approximation used for the field of the atom.

The total cross section per atom is given from (7) by

$$\pi\rho^2 = 2\pi K^2 \int_0^1 \frac{g(y)}{y^3} dy$$

i.e.

$$\pi\rho^2 = 1.083 \cdot 10^{-23} \int_0^1 \frac{g(y)}{y^3} dy \tag{9}$$

In order to proceed any further the average values of the Legendre polynominal must be evaluated. Murphy's expansion in power of $\sin \theta/2 = y$ is used.

$$P_\ell(\cos\theta) = \sum_0^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2}\, y^{2k} \tag{10}$$

Therefore the average value after one collision is

$$\left\langle P_\ell(\cos\theta_1)\right\rangle_{AV} = \frac{2\pi K^2}{\pi\rho^2} \sum_0^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2} \int_0^1 g(y)\, y^{2k-3}\, dy \tag{11}$$

Hence

$$\left\langle P_\ell(\cos\theta_1)\right\rangle_{AV} = 1 - Q_\ell = 1 - 2\left(\frac{K^2}{\rho^2}\right)\left[\ell(\ell+1)\int_0^1 g(y)\, y^{-1}\, dy - \sum_2^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2}\int_0^1 g(y)\, y^{2k-3}\, dy\right] \tag{12}$$

Hence from (5)

$$G_\ell = \exp\left\{-2\pi K^2 N d\left[\ell(\ell+1)\int_0^1 g(y)\, y^{-1}\, dy - \sum_2^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2} \int_0^1 g(y)\, y^{2k-3}\, dy\right]\right\} \tag{13}$$

Hence from (4)

$$f(\theta d) = \frac{1}{4\pi}\sum (2\ell+1)\, P_\ell(\cos\theta) \exp\left\{-2\pi K^2 N d\left[\ell(\ell+1)\int_0^1 g(y)\, y^{-1}\, dy - \sum (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2}\int_0^1 g(y)\, y^{2k-3}\, dy\right]\right\} \tag{14}$$

In evaluation of this, it is legitimate to omit the screening factor in the second integral as long as ℓ does not become too large. Under these circumstances

$$\sum_2^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2}\int_0^1 y^{2k-3}\, dy = \sum_2^\ell (-1)^k \frac{(\ell+k)!}{(\ell-k)!\,k!^2}\cdot\frac{1}{(2k-2)} = \ell(\ell+1)\left(\frac{1}{2}+\frac{1}{3}+\cdots+\frac{1}{\ell}\right) \tag{15}$$

For the first integral

$$\int g(y)\, y^{-1}\, dy = \log \xi \tag{16}$$

and considering, say the Born approximation to the field

$$\log \xi = \log \frac{1.21\, a}{\lambda} \tag{17}$$

where λ is the wavelength associated with the electron

$$a = \frac{a_0}{Z^{1/3}}$$

$$a_0 = \frac{\hbar^2}{me^2} = \text{Bohr radius of hydrogen}$$

Hence on substituting (15) and (17) (into 14)

$$f(\theta d) = \frac{1}{4\pi} \sum (2l+1)\, P_l(\cos\theta) \exp\left\{-2\pi K^2 N d\, l(l+1) \left[\log\left(\frac{\hbar^2}{me^2 Z^{1/3}} \cdot \frac{1}{\lambda}\right) - \frac{1}{2} + \text{----} + \frac{1}{l}\right]\right\} \tag{18}$$

for not too large values of l .

For a 100 kev electron once more

$$\log \frac{\hbar^2}{me^2 Z^{1/3}} \cdot \frac{1}{\lambda} = \log_e 22.245 \tag{19}$$

$$= 3.1 \tag{20}$$

So for the 100 kev electron using (2) and (8)

$$f(\theta d) = \frac{1}{4\pi} \sum (2l+1) P_l(\cos\theta) \exp\left\{-1.083 \cdot 10^{-23} N d\, l(l+1)\left[3.1 - \left(\frac{1}{2} + \text{---} + \frac{1}{l}\right)\right]\right\} \tag{21}$$

If the gas is considered as being at 200 micron pressure, i.e., $N = 3.17 \times 10^{14}$ mol/cc for a temperature of 300°K.
So

$$f(\theta d) = \frac{1}{4\pi} \sum (2l+1) P_l(\cos\theta) \exp\left\{-4.10^{-9} d\, l(l+1)\left[3.1 - \sum_{n=2}^{l} \frac{1}{n}\right]\right\} \tag{22}$$

and this is assumed for not too large values of ℓ , say no larger than 30. Taking an increase in pressure of one order of magnitude to 2 mm of Hg the

$$f(\theta d) = \frac{1}{4\pi} \sum (2\ell+1) P_\ell (\cos\theta) \exp\left\{-4.10^{-8} d(\ell+1)\ell\left[3.1 - \sum_{n=2}^{\ell} \frac{1}{n}\right]\right\} \qquad (23)$$

So it is seen that the scattering is greater in the regions of higher pressure i.e., in the shock wave -- as is to be expected.

This treatment is valid for small angle of multiple scattering and for not too high value of ℓ . Another approximation which is made is that the thickness of the gas scatter is equal to the path length of the electron, but this is not too important an approximation.

Space-charge spreading of the beam can be shown to be negligible.

Note that the function $f(\theta d)$ has been normalized to unity over a sphere and so if there is a flux of M electrons in the electron beam the distribution at an angle θ and distance d is $Mf(\theta d)$.

One then evaluates $f(\theta d)$ for values of θ , and computes the mean square scattering angle from a criterion for f , such as that f shall be $< .1$. This is obviously tedious.

If the sums are evaluated approximately,

$$\bar{\theta}^2 = \frac{d 4\pi N Z(Z+1) e^4 (1-\beta^2)}{c^4 m \beta^4} \ln\left[4\pi Z^{1/3}(Z+1) N d \left(\frac{\hbar}{mv}\right)^2\right] \qquad (24)$$

or

$$\bar{\theta}^2 \sim \frac{Nd}{E^2} \ln\left[\frac{Nd}{E}\right] \qquad \text{for low energy.} \qquad (25)$$

then: 1. $\theta \sim \frac{1}{E}$. This implies that the scattering angle varies inversely with energy.

2. If the beam enters a region of higher density, such as a shock, the ratio of the thickness of the shock to the distance traveled prior to entrance must be in the inverse ratio of the gas density if θ^2 is to be at least as large. If it is, however, no major effect on beam spread will exist. The criterion of effectiveness is contained in (eq. 25) and depends upon the accuracy with which a difference in θ^2 may be detected.

3. If one is to determine N (gas density) from θ^2 , one must have an independent measure of t .

APPENDIX B

THE ELECTRON BEAM AS A DIAGNOSTIC IN HYPERVELOCITY FLOWS

The problems associated with gasdynamic measurements and the determination of the chemical state in hypervelocity airflows are complex. The requirements of hypersonic flow simulation ensure that most such experimental facilities operate in a density regime below the sensitivity limit of ordinary optical interferometry. The requirements on the sensitivity of pressure measurement are also extremely demanding. These data, however, even if available, are inadequate to specify the state of a gas flow which may be in vibrational, chemical and ionizational nonequilibrium. It is imperative that information on the thermal and caloric state of such gas flows be obtained and all methods of potential value should be investigated. The onus, then, is on the experimentalist for ingenuity in the modification and application of diagnostic techniques from related sciences.

Several such applications have been made: from gaseous electronics, the free-molecule Langmuir probe for the measurement of electron temperature and electron number densities in ionized flows; through spectroscopy, the number density of O_2 and NO molecules may be inferred from their absorption spectra in the vacuum ultraviolet. The use of a high-energy electron beam to excite emission from low-density air has already been discussed. The emission is almost exclusively that from the N_2^+ ion first negative system. Fortunately, the transitions involved in the excitation (particularly) and deexcitation of this system are fairly simple. Consequently, by observation of the beam-excited emission spectra, it is possible to measure the rotational and vibrational temperature of the nitrogen molecules as well as the number density of the nitrogen molecules in the gas. Since the rotational and translational degrees of freedom are in equilibrium for most flow situations, the rotational temperature will be the same as the local gas temperature.

The physical principles underlying the spectroscopic measurement of gas temperature and number density have been fully described by Muntz.[5] Briefly, the theory indicates that the emission spectra may be interpreted to give the rotational and vibrational temperatures in the following manner. The rotational temperature is obtained by measuring the relative intensitites of the rotational lines (fine structure) in the vibrational bands. The relative intensity of each line is then plotted as a function of its rotational quantum number for the whole band. The resulting plot is a straight line and the rotational temperature may be determined from the slope of this line.

The vibrational temperature is obtained by measuring the relative intensities of the vibrational bands in the emission. This intensity ratio may be predicted theoretically as a function of the vibrational temperature and a plot of the relationship affords the basis for experimental measurement. The intensity ratio of the (1, 0) and (0, 1) bands of the first negative

system of N_2^+ has been used successfully. The number density of the electronic ground state N_2 molecules is obtained from the spectroscopic records used for the rotational and vibrational temperature measurements. The number density may be calculated by measuring the intensity of a particular rotational line in a vibrational band. A calibration curve is first established by measuring a line intensity in the (0, 0) band versus N_2 molecule concentration at room temperature. The number density at any other temperature and pressure is then obtained from this calibration curve, provided the rotational temperature is known.

The above method of number density measurement differs from that discussed in the body of the text in that the total light emission from the beam is not observed. This has the distinct advantage that only the light from a particular radiating system is resolved while the light from other radiating species that may also be present will not interfere and introduce errors. In the analysis, it has been assumed that the excitation-re-emission process is unaffected by gas kinetic collisions. Since the mean lifetime of the N_2^+ excited state is about 10^{-9} sec, the upper limit on gas density is that for which the mean molecular collision period is of the same order. In this respect, the spectroscopic method further allows the emission from short-lived electronic states only to be selected.

Several experimental determinations of the rotational and vibrational temperature and nitrogen molecule concentration have been made in low-density flows of nitrogen,[5] with reported accuracies in measurement of 2%, 10%, and 8% respectively. Since the flow configurations investigated were steady, the emission spectra were recorded on photographic film.

For application of short-duration facilities (hot shot tunnels or shock tunnels), the principle of the method is, of course, unchanged, though slight differences in technique are necessary. Owing to the short flow times involved, sufficient exposure times for spectrographic plate or film are not possible. However, observation of the beam-induced emission may be adequately accomplished by the use of phototubes or photomultipliers.

The use of photomultipliers imposes no difficulties of spectral resolution for vibrational temperature measurements since the relative intensities of complete vibrational bands are measured. In the case of number density determination, the measurement of a particular rotational line intensity imposes a severe requirement on resolution for any photomultiplier. However, the ground state number density of the N_2 molecules may also be measured, and with greater accuracy, by observing the intensity of the complete rotational line structure; i.e., the combined intensities from all the rotational lines in a given vibrational band. The room temperature calibration must, of course, be performed in the same way.

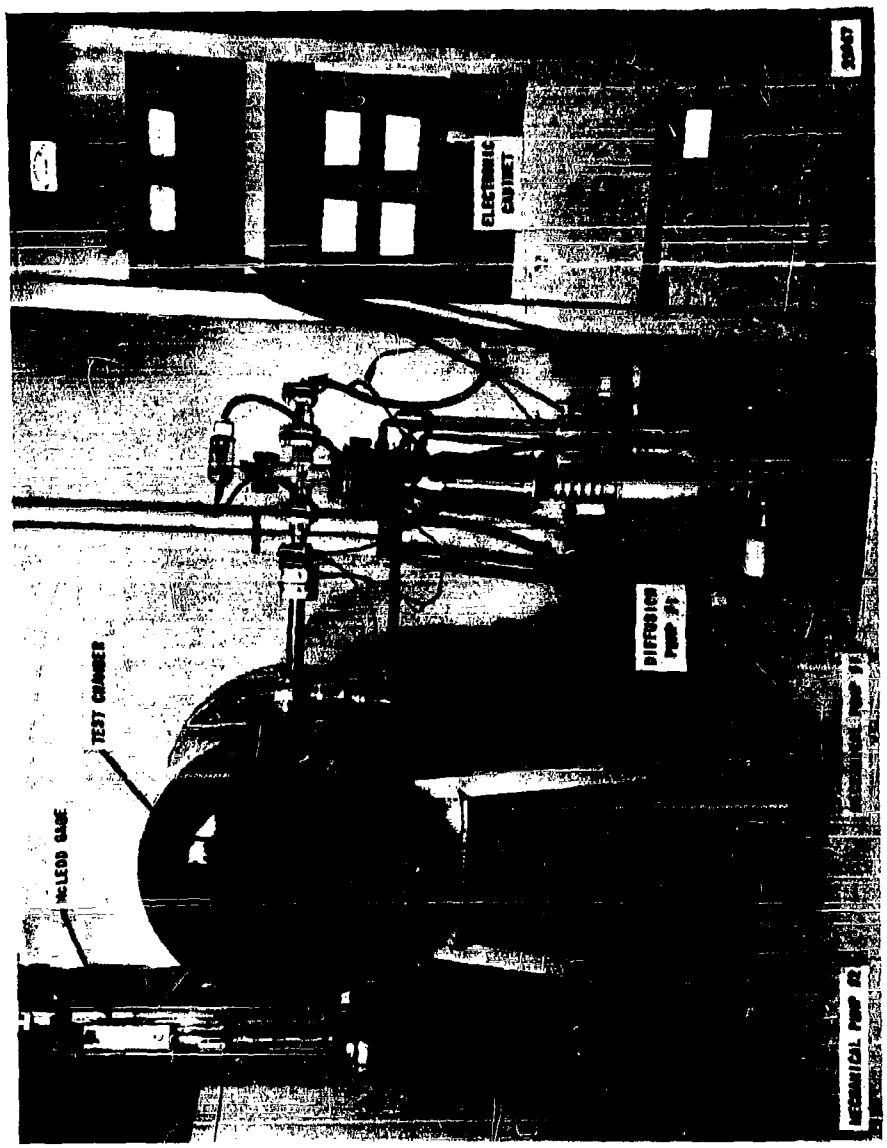
In this manner, no correction for the rotational temperature is necessary since the energy distribution over all rotational quantum levels is observed. As before, however, a correction must be applied if the vibrational temperature is high. At a calibration temperature of 300°K, all the N_2 molecules are in their ground vibrational state. Consequently, in the case of high vibrational temperatures, it is necessary to know the number distribution of molecules in the higher vibrational states of the excited ion. However, for a Boltzmann distribution of the vibrational energies, a correction to the calibration curve may be calculated in a fairly straightforward manner from available Franck-Condon factors.

A further change in technique is necessary for the measurement of rotational temperatures in short-duration flows. Again, resolution limitations with photomultipliers will prevent the measurement of the relative intensities of successive rotational lines. However, by the use of narrow band pass filters or monochromators, the ratio of the sum of the intensities of three or four lines at high quantum numbers may be measured in the same vibrational band. Such an intensity ratio may be calculated and plotted as a function of rotational temperature.

In summary, the rotational and vibrational temperature and number density of nitrogen molecules may be measured in a gas flow by spectroscopic observation of electron beam excited emission. The method is applicable to any flow containing nitrogen or to which nitrogen is added as an "indicator" gas. The technique of measurement is applicable to short-duration flows subject to the development of a suitable photomultiplier-recording spectroscope.

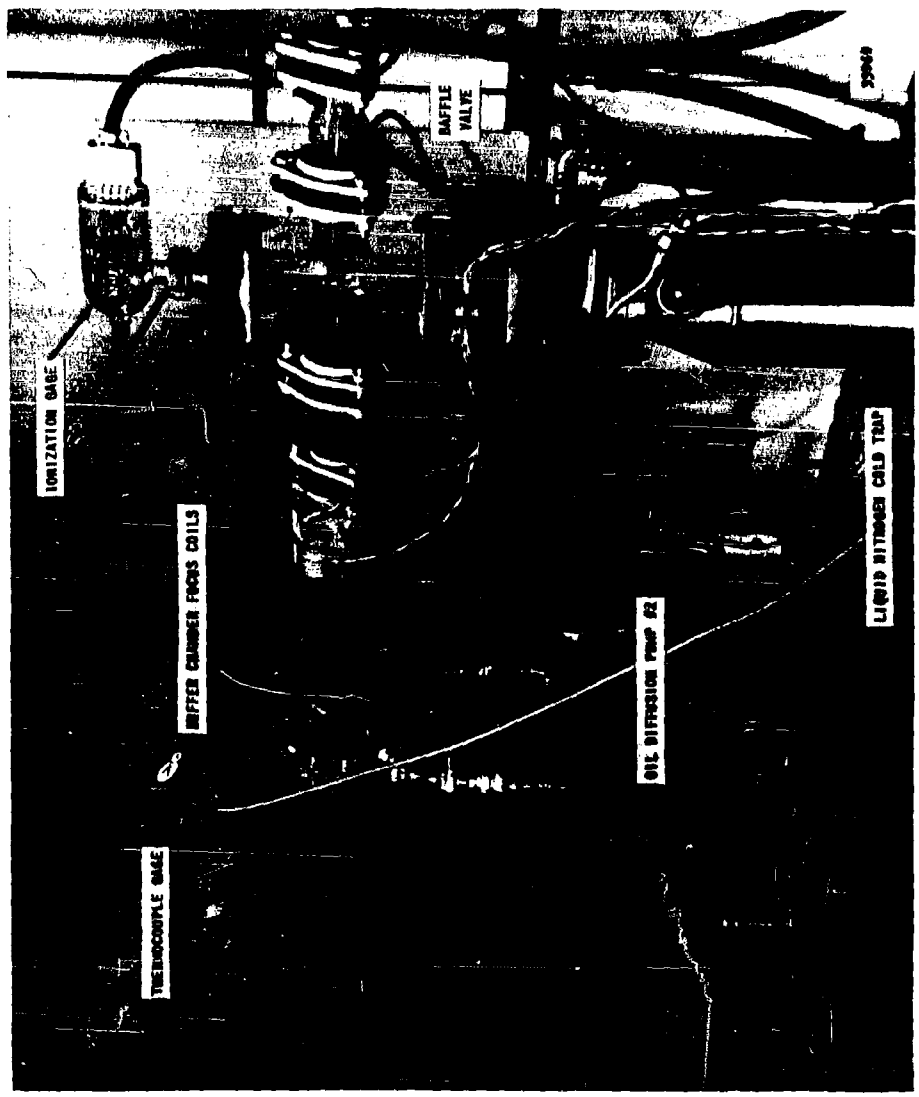
TABLE I

PICTURE NUMBER	EX. TIME SEC.	f NUMBER	I_K μAMPS	I_B μAMPS	E KV	PRESSURE MICRONS
GROUP I	CONSTANT VOLTAGE-VARIABLE DENSITY					
122	1/2	5.6	1500	392	9	2
127	1/2	16	1500	365	10	16
133	1/2	22	1500	298	9	30
139	1/2	32	1500	305	10	62
GROUP II	CONSTANT DENSITY & VOLTAGE, VARIABLE EXPOSURE					
82	4	5.6	1450	480	10	30
83	2	5.6	1450	480	10	30
84	4	11	1450	480	10	30
85	2	11	1450	480	10	30
86	1	11	1450	490	10	30
87	1/2	11	1450	490	10	30
88	1/2	16	1450	490	10	30
89	1/5	16	1450	490	10	30
SCANNED PICTURE						
183	8.5	4.5	1600	430	21.5	65
ATTENUATION AT 65 MICRONS 20 KV						
149	1/2	16	1500	275	20	65
METAL MODEL - 206 GLASS MODEL 226						
206	5	4.5	1600	380	20	32
226	5	4.5			18	32



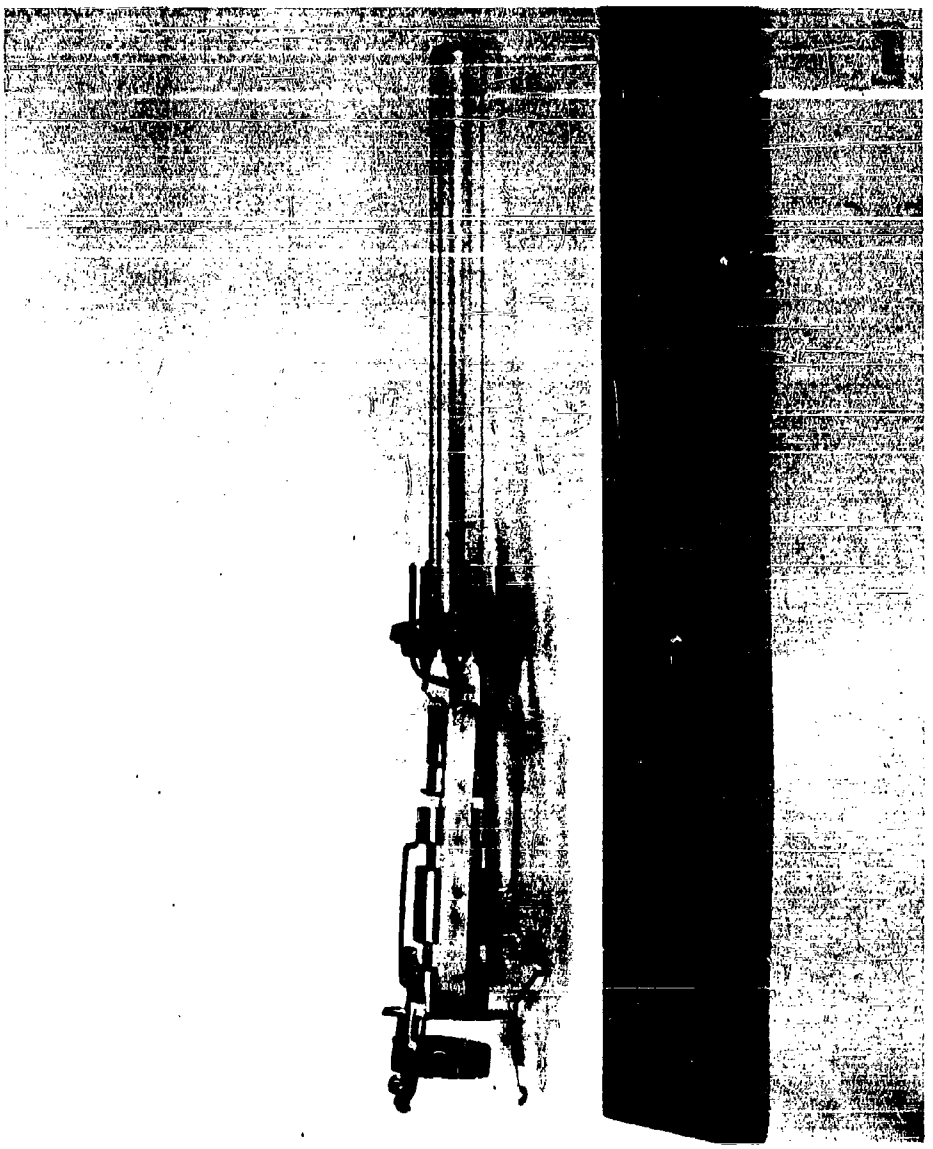
GENERAL VIEW OF APPARATUS

Figure 1

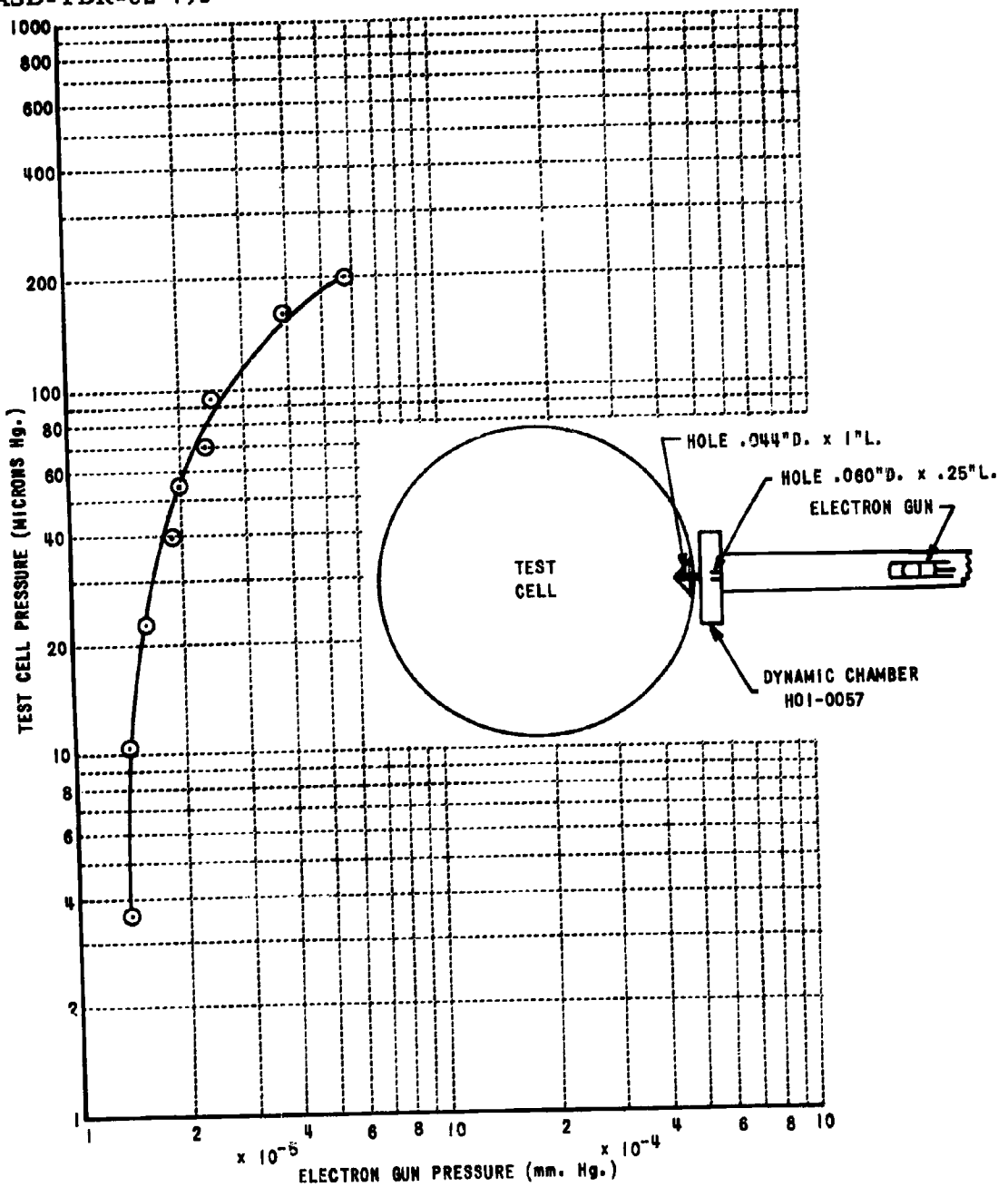


ELECTRON GUN ASSEMBLY

Figure 2

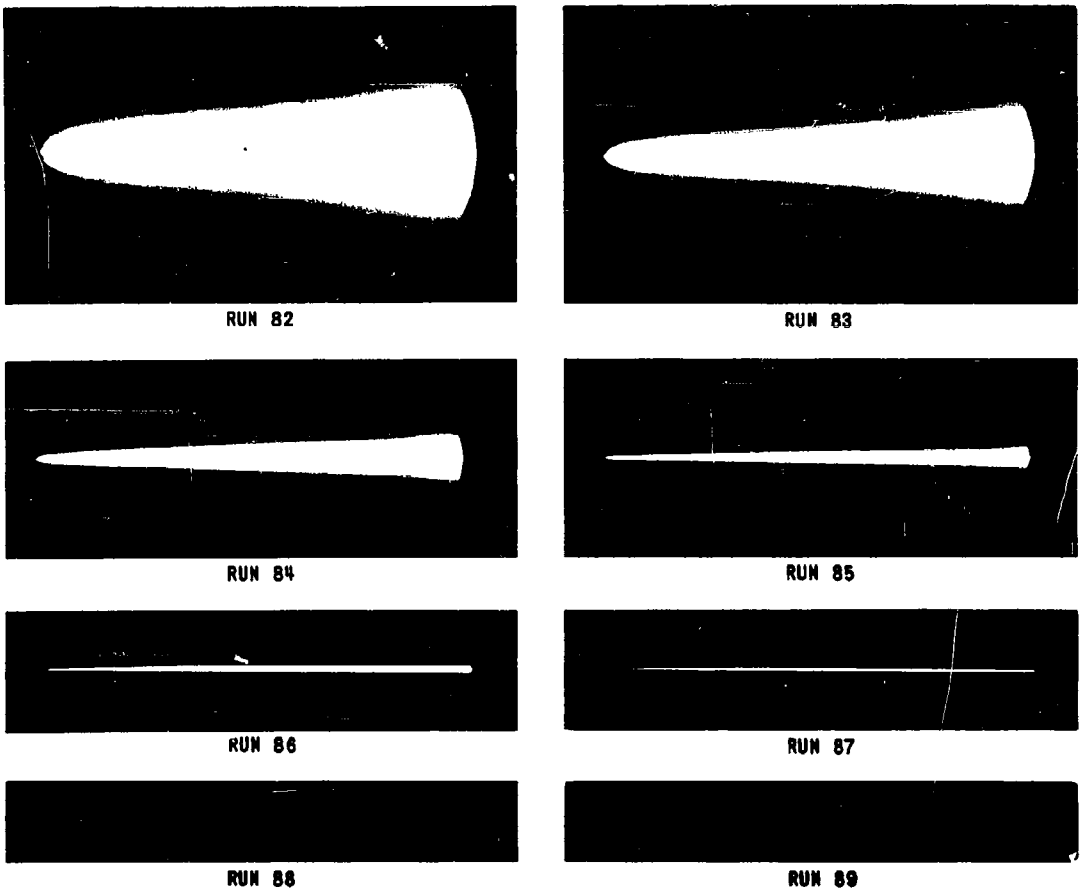


ELECTRON GUN
Figure 3



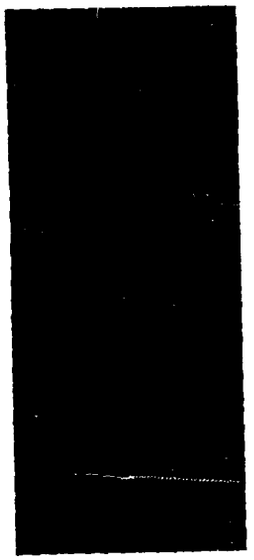
DYNAMIC CHAMBER PRESSURE PERFORMANCE

Figure 4

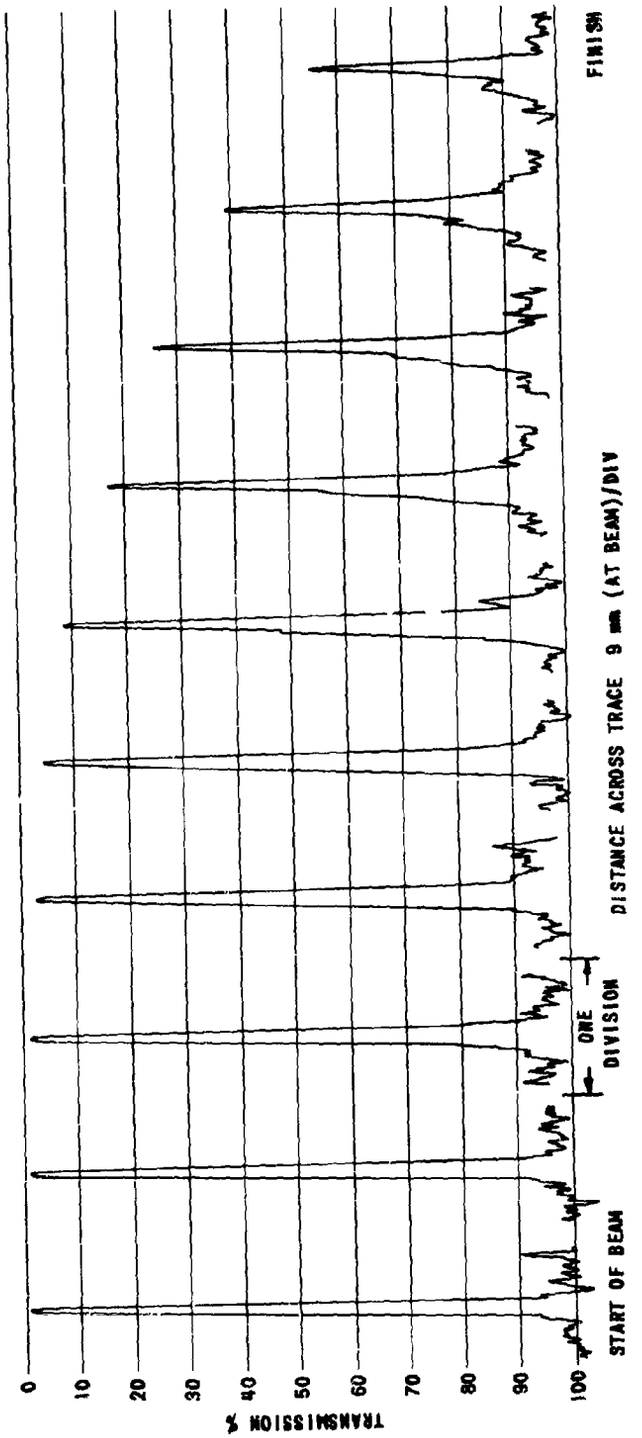


EFFECT OF VARYING EXPOSURE
Figure 5

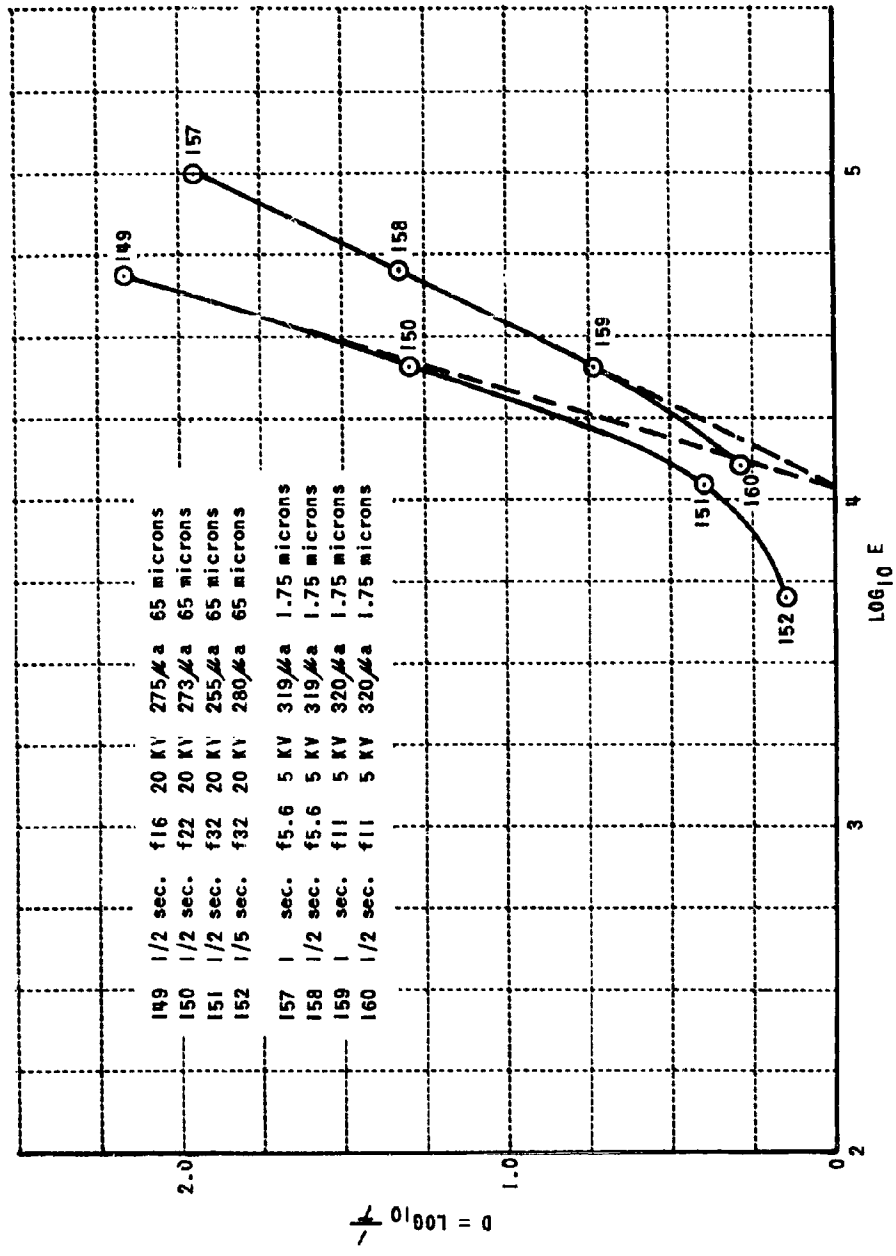
EFFECT OF VARYING GAS DENSITY WITH ADJUSTED EXPOSURE
Figure 6



RUN 149, 20 KV, 65 MICRONS
Figure 7

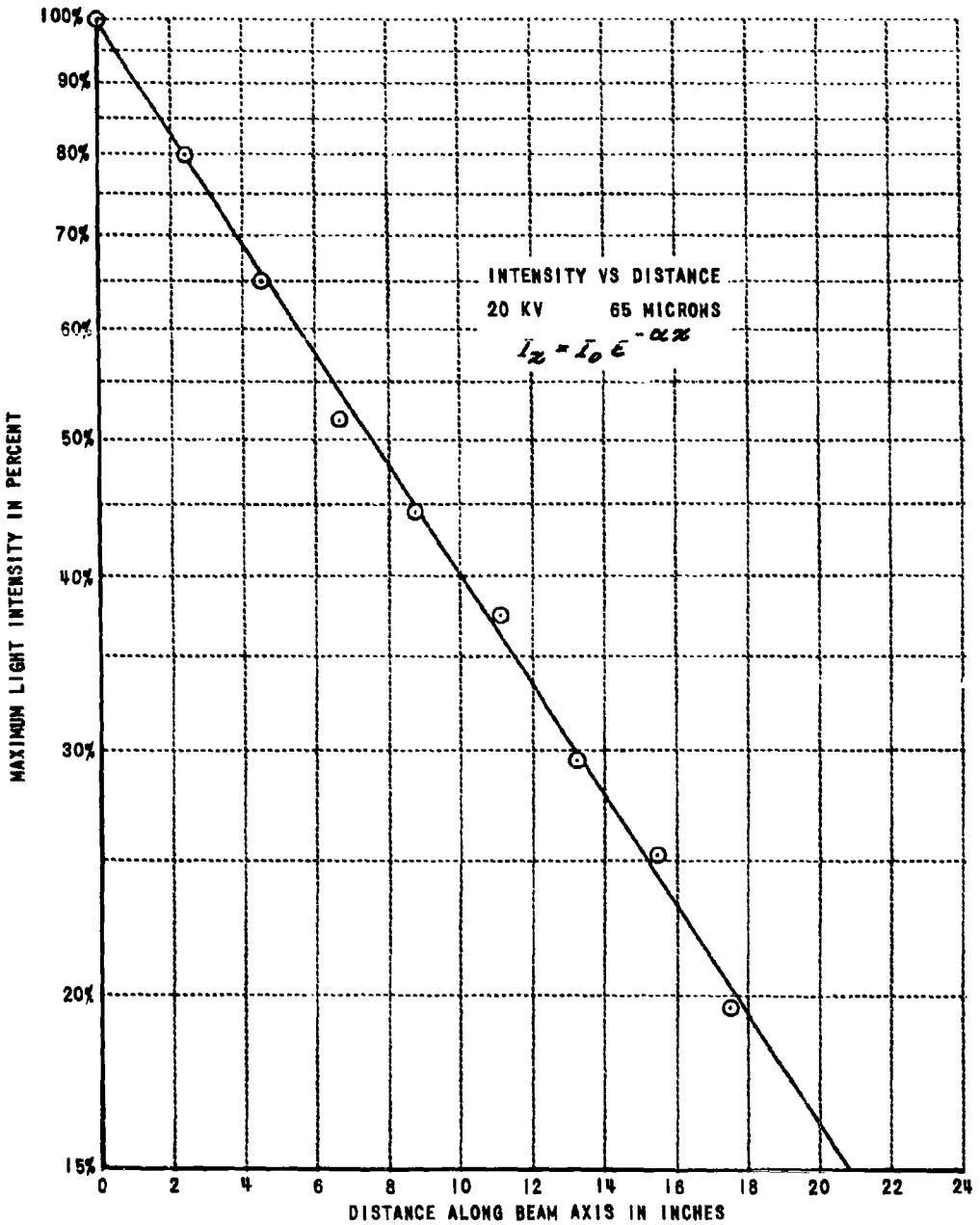


MICRODENSITOMETER RECORD
Figure 8



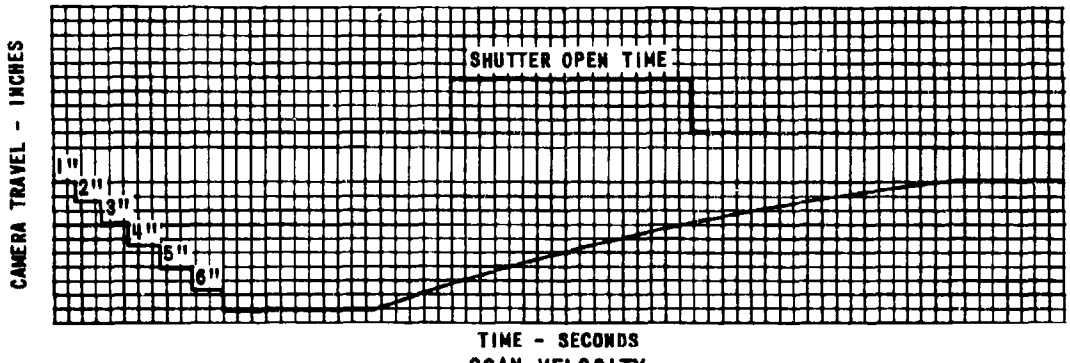
D-LOG E CURVES FOR ROYAL BLUE FILM SHOWING VARIATION DUE TO DEVELOPMENT

Figure 9



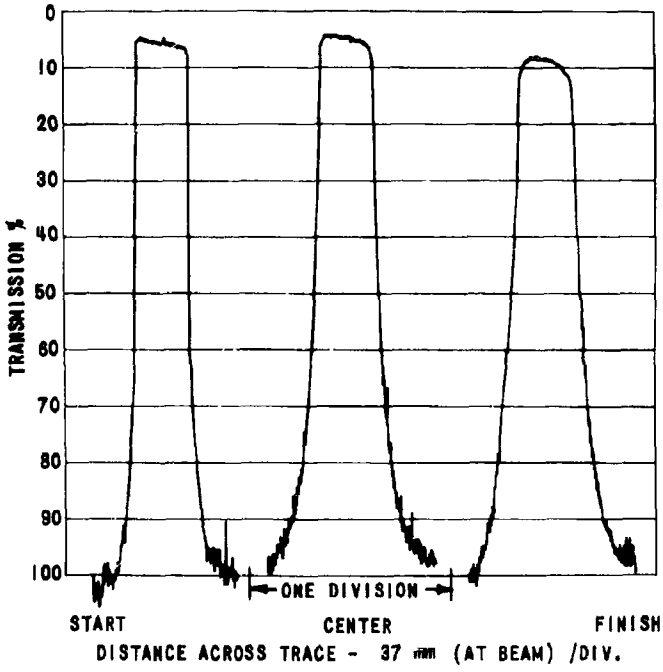
ATTENTUATION OF UNSCANNED BEAM

Figure 10

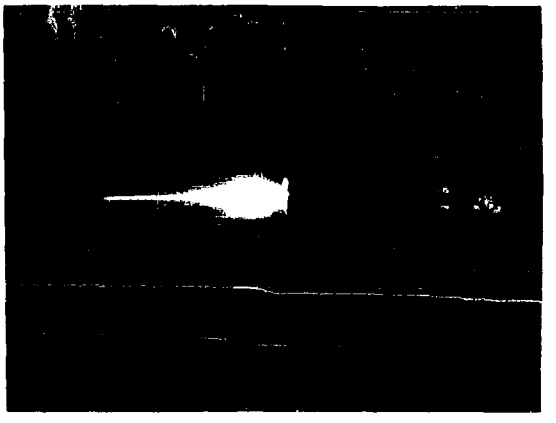


SCAN VELOCITY
Figure 11

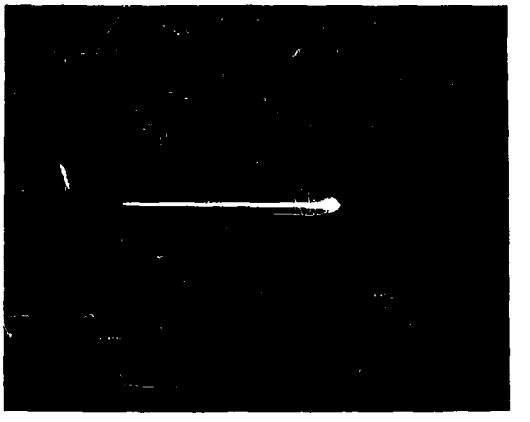
EFFECT OF SCANNING THE BEAM
Figure 12



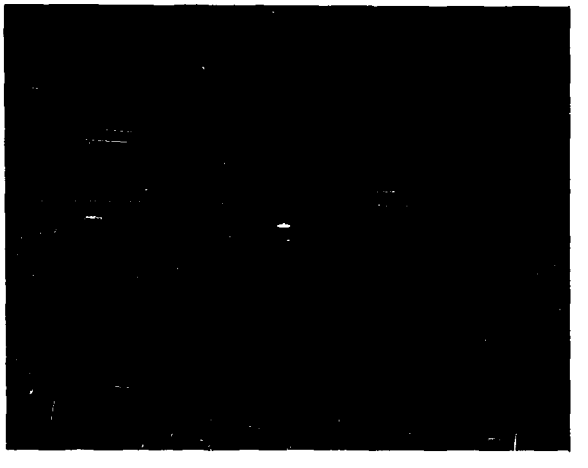
MICRODENSITOMETER RECORD
Figure 13



METAL MODEL IN TEST CHAMBER
Figure 14



GLASS MODEL IN TEST CHAMBER
Figure 15



AIR JET DIRECTED AT BEAM
Figure 16

Aeronautical Systems Division, Dir/Engineering Test, Aerodynamics Division, Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-793. FLOW VISUALIZATION AND QUANTITATIVE GAS DENSITY MEASUREMENTS IN RAREFIED GAS FLOWS. Final report, Dec 62, 34p. incl illus., table, 14 refs.

Unclassified Report

The use of an electron beam to stimulate emission from a gas with the resultant beam intensity providing a measure of point-by-point gas density, has been investigated. The tests have been conducted in the 1 to 200 micron pressure range, at standard temperature, employing a 5 to 20 kev electron beam. Analysis was performed by photographing the beam at conditions of varying density, and examining the film by means of a microdensitometer. A low-cost electron gun capable of projecting a 20 kev, 500 microampere beam across a 24-inch test chamber was successfully developed. The results of the program indicate that at the beam voltages employed, scattering of the electrons by the atoms of the gas severely limits the particular technique used. The analytical and experimental results of the program indicate that gas density measurement and flow visualization may be possible by employing a more energetic electron beam. By observation of the beam-excited emission spectra, it is possible to measure the rotational and vibrational temperature of the nitrogen molecules as well as the number density of nitrogen molecules in the gas. Further investigation of this latter electron beam technique as a diagnostic technique in hypervelocity flows, is recommended.

(over)

1. Gas density measurements
2. Gas flow
3. Experimental and Analytical results
I. AFSC Project 1426, Task 142610
II. Contract AF 33(616)-8145
III. Cornell Aeronautical Lab., Inc., Buffalo, N. Y.
IV. R. C. MacArthur, L. M. Stevenson, J. Budell
V. Aval for OTS
VI. In ASTIA collection

Aeronautical Systems Division, Dir/Engineering Test, Aerodynamics Division, Wright-Patterson AFB, Ohio.
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